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Energizing wireless sensor networks by energy harvesting systems: Scopes, challenges and approaches

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ABSTRACT

As the wireless sensor networks (WSNs) technology has great advancement, small and smart WSN systems now can be used for more complicated and challenging applications. WSNs investigation has primarily believed the use of a convenient and inadequate energy source for empowering the sensors. A sensor becomes useless in the absence of energy and becomes unable to contribute to the utility of the network as a group. Therefore, extensive efforts have been used in finding energy-efficient networking protocols for increasing the life span of WSNs. However, there are promising WSN applications where the sensors are obligatory to work for a long time after their deployments. In these cases, batteries are tough or impractical to replace/recharge. Although, a little amount of power is required for these applications, the useable lifetime of WSNs is decreased by the gradual degradation of the batteries. With the motivation of raising the usable WSNs around us and to value a number of economic and environmental limitations, researchers are looking for new green and theoretically unlimited energy sources. Harvesting of energy from the ambient energy is the basement of these new sources. Energy harvesting devices efficiently and effectively capture, accumulate, store, condition, and manage this energy and supply it in a form that can be used to empower WSNs. This harvested energy can be an alternative energy source for adding-on a principal power source and thus increase the consistency of the whole WSN by preventing the disruption of power. A great deal of research has been reviewed and specific ranges of applications have been found. Though there are challenges to overcome, different researchers have taken different approaches to solve those. In this review, we have emphasized on different scopes, challenges, ideas and actions of energy harvesting for WSNs.

Contents

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1. Introduction

After the invention of batteries by Alessandro Volta in 1799, it becomes the world's first practical electricity source. The progress continued until the cabling of cities demoted batteries to mobile applications in late 1800 [1]. People living in the early 1900s have used enormous portable radios for picnics and other events by using the batteries [1,2]. As the electronics technology improved, the size of batteries becomes smaller with higher capacity and it enables today's wireless and mobile applications explosion. Though cost-effective batteries are a key reason behind this growth, they furthermore bound its infiltration; pervasive computing's dream of wireless sensors everywhere is accompanied by the nightmare of battery replacement and disposal.

A collection of sensing nodes which are connected through wireless channels formed a wireless sensor network (WSN) [3,4]. In a WSN, the nodes communicate with each other through wireless channels in order to accumulate spatially distributed data about their environment [5]. Such kind of WSN provides superior quality data than individual sensor in different applications, such as process monitoring, natural environmental monitoring, security and surveillance [6,7]. WSN is considered as the third wave of uprising in wireless technology [8]. WSN promises to provide a significant positive impact on many parts of human life, such as more effective use of resources, good understanding of human behavior, natural and engineering systems, and better safety and security [9]. Pervasive computing also has some probable negative impacts on the environment, mostly in physical waste and energy consumption [10].

So, as to be cost effective in different applications, it is necessary to choose low cost and low maintenance sensor nodes [11] regarding sensor calibration, wrapping for persistence in severe environments and mainly, the efficient and continuous supply of power [12]. Nowadays, the performance of battery technology is much enriched and on the other side, the requirement of power for electronics is reduced [13,14]. However, these are not capable of keeping pace with increasing demands of different WSN applications. For this reason, interests are growing in developing such systems, which are proficient of extracting necessary power supply from different green sources and this energy extraction process is called as energy harvesting [7]. Fig. 1 shows an optimized energy harvesting block diagram. In this paper, we have provided an overview of the scopes, challenges and approaches of energy harvesting from the suitable sources for using in WSN nodes.

2. Applications of wireless sensor network

A huge number of sensor network applications have been reported ranging from initial research investigations [6]. A broad range review of the applications is given in [16] as the basis of the design space model.

2.1. Environmental monitoring

Environmental monitoring is one of the widely considered areas for the application of WSN. A lot of researches have been conducted in this area. Measurement of glacier dynamics [17], sea bed pressure, temperature, conductivity, current, and turbidity monitoring [18], observation of temperature, salinity, and current profile of the upper ocean [19], monitoring of the grape growing conditions [20], etc., are some of the examples of applications of WSN in environmental monitoring.

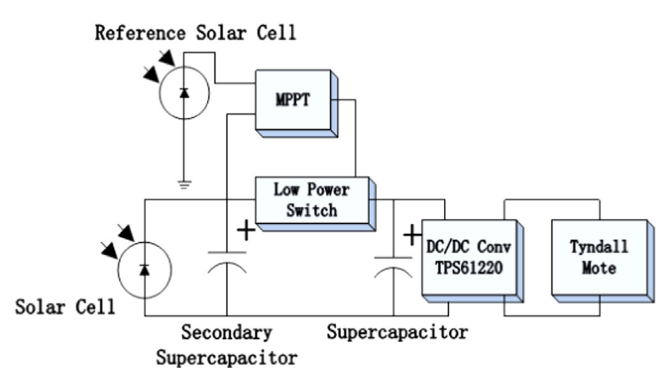

Fig. 1. Optimized energy harvesting system block diagram [15].

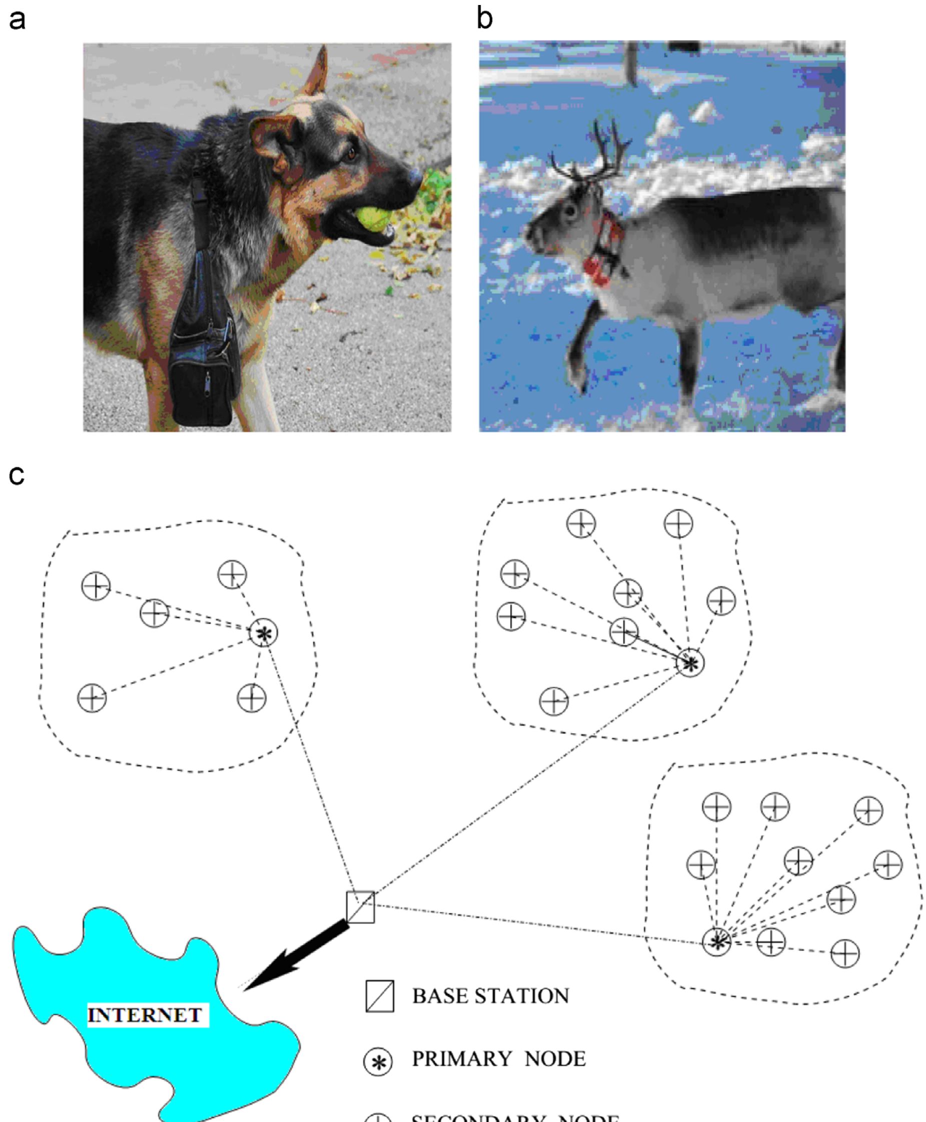

Fig. 2. A secondary node (a) in a hip bag around a dog neck in a Spanish courtyard, (b) mounted on a reflective collar around a reindeer neck in Northern Sweden, and (c) network description [24].

Table 1
Energy consumption [24].

Working node	Peripheral	Consumption
Sleep	None	20 μA
Standard	None	20 mA
Standard	GPS	150 mA
Standard	433 MHz radio	22 mA
Standard	166 MHz radio	146 mA

Table 2
Acceptable payload weights for relevant species [26].

Species	Adult weight (g)	Allowable device weight at 3% (g)	Allowable device weight at 5% (g)
Swift Parrot	77	2.31	3.85
Pigeon	280–600	8.4–18	14–30
Bald Eagle	3000–7500	90–225	150–375
Common Loon	3600–5500	108–165	180–275

2.2. Animal tracking and control

Tracking and controlling the movements of domestic and wild animals presents interesting challenges in WSNs [21]. Many researches have also been conducted in this field. The breeding behavior observation [22], the observation of the roaming of wild animals over a very large area [7,23], monitoring the behavior of animals and controlling it [7,24,25], etc., are the examples of the use of WSN in animal tracking and control. In all of the cases, the network of nodes is connected to a base station.

A wireless localization technique based on stochastic movements [24] is shown in Fig. 2.

When no peripheral is active and the microcontroller remains in sleep mode, the minimum consumption becomes 20 A at 3.3 V. For each peripheral, the typical consumption when active is shown in Table 1 [24].

During animal tracing, the weight of the tracing device is needed to be considered. In [26], the author has given an idea of weight for birds, which is represented in Table 2.

2.3. Safety, security and military Applications

WSNs have been established to support rescue teams in saving people concealed in avalanches [7,27], trailing of military vehicles using networks of nodes by un-manned aerial vehicle (UAV) [7], anti-tank land-mines with self-monitoring capability [7,28], determination of the location of a sniper and the direction of the bullet [7,29], monitoring of buildings and emergency response personnel with the goal of improving security in dealing with fires and other life threatening situations [7,30], etc. In [31], a power electronic circuit is presented for extracting usable electrical power from a backpack-based energy harvesting system and the power output for different weights is presented in Fig. 3. Here, electricity generation for 40 lbs, 60 lbs, and 80 lbs is presented due to different walking speeds. From this figure, it is very clear that the generation of electricity is high for higher speed as well as for higher weight.

2.4. Built environment

A major WSN application is the core environmental condition monitoring and monitoring the variety of heating, lighting, etc., in response to human occupancy and activity [32]. A WSN is developed in [7,33] for monitoring the power consumption in a large office building with the aim of detecting the locations or the devices of high power consumption.

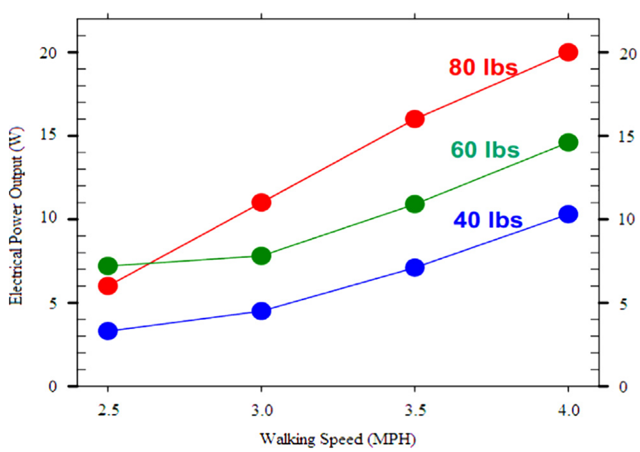

Fig. 3. Electricity generation during walking [31].

2.5. Health

Health applications for WSNs contain patient monitoring, drug administration, tracking of patients at home [7,34,35] and doctors in hospitals. Body sensor networks [7,36] are used in the medical sector. The wireless monitoring of patients and data about the patient's condition can be analyzed for abnormal reaction and side effects [37]. An analysis of the performance of medical sensor body area networking is presented in [7,38], which also endorsed the advantage of using IEEE 802.15.4 and ZigBee for medical sensor technologies. Also, WSN for rehabilitation have been used in several clinical applications. In [39], the authors classified the existing solutions from a process point of view and they divided them into two main classes that is described in Fig. 4.

Also, using WSN for rehabilitation supervision brings some benefits. WSN and visual motion tracking systems have different characteristics that are summarized in Table 3 [39].

Power dissipation for different medical applications [40] is summarized in Table 4.

3. Scopes of energy harvesting for wireless sensor network

As energy is the major concern, it is predictable that the emphasis of research has been on power management along with some other topics.

3.1. Power management

In this respect, maximum efforts are given to supplement the on-board battery by using energy harvesting [41]. Consequently, for maximizing the benefits of harvested energy, efficient power management is important. Power consumption data for some common energy monitoring sensors are given in Table 5.

Energy harvesting power management system has been presented in [43]. Harvesting aware power management (HAPM) strategies have been presented for energy harvesting systems that retain devices operated in an energy neutral mode. The authors have been studied the advantages and disadvantages for three unlike approaches of HAPM, which are duty cycling, frequency scaling and maximum power point tracking. The conclusion is that the best choice is the dynamic or adaptive power management for energy harvesting systems.

A significance of using energy harvesting devices in WSN is that traditional metrics cannot be used for power management [44].

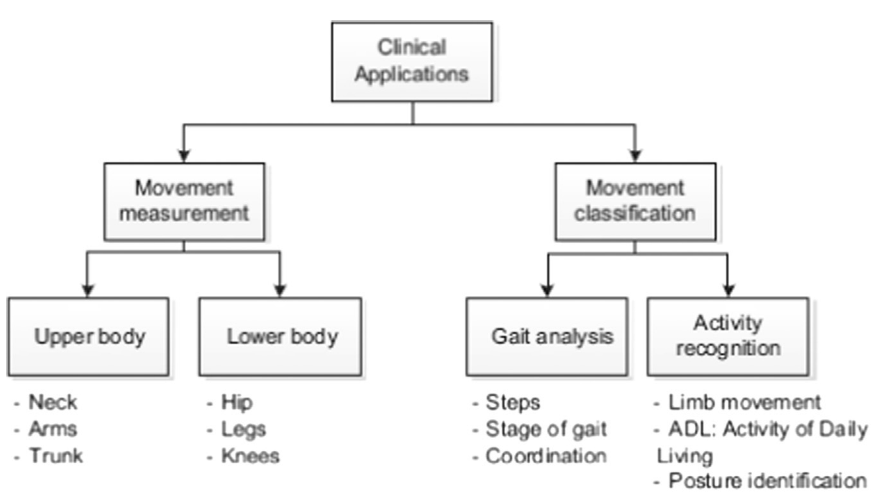

Fig. 4. Taxonomy of WSN clinical rehabilitation applications [39].

In its place, imminent energy availability statistics are required for making decisions about optimal routing [45]. To accomplish this, an environmental energy harvesting framework [46] has been suggested to acquire information about energy environment. Using this information, the performance of WSN can be improved by efficiently exploiting the energy resources. A power management system along with an analytical model has also been developed [47] for the prediction of various performance metrics, adaptive duty cycles and other correlated features. A more reasonable approach is to add a power management system between the harvesting source and the load, which attempts to satisfy the energy consumption profile from the available generation profile shown in Fig. 5.

Another method is proposed by assuming two transmission modes of sensors [48]. Therefore, researchers have great chances to improve the power management for efficient WSN use.

3.2. Data delivery scheme

The delivery process of data from a sensor to the sink generally includes two significant tasks: accessing to the medium and advancing the information to the succeeding step headed for the sink. Energy conservation remains as the main objective of the WSN networking protocol scheme. A latest study on WSN protocols can be found in [49].

A polling-based medium access control (MAC) protocol has been proposed for the use of sensors powered by ambient vibrations, but optimization has not done [50]. Cooperative transmission protocols for wireless communications have also been suggested for energy harvesting in wireless sensor nodes [51].

Directed Diffusion is one of the initial WSN routing protocols, which has been revised to integrate data about the supply of power (solar or battery power) of nodes [52]. The results show that the performance of solar-aware variant is better than the shortest path routing. However, the environment can provide a limited amount of power and therefore, a routing algorithm has to be established, which considers the actual environmental conditions [53]. The key idea is to model the flow network and attain appropriate explanation by resolving the max flow problem for maximizing throughput. The alternative solution integrates the energy replacement ratio hooked on the cost metric during routes computing [54].

3.3. Topology and connectivity

Power control is one of the important issues for maintaining connectivity over topology control [55]. If the harvested energy is not sufficient for supplying continuous power to the sensor node, the nodes have to go to sleep for battery charging. This modifies the network topology and connectivity. Different sleep and wakeup performance strategies are based on different factors, for instance channel state, battery state and environmental conditions and these are analyzed in [56]. Game theory can also be applied for finding the optimal parameters for the scheme of sleep and wakeup to compromise between packet blocking and dropping probabilities [57]. Another analytical framework has also been presented in [58] for the estimation of various statistical properties of the system. It has also been presented that sensor networks

Table 3
Comparison between visual motion tracking and WSN based solution for rehabilitation supervision [39].

Characteristic	Visual motion tracking	WSN based solutions
Cost	High	Low
Accuracy	High	Good
Complexity	High	Low
Automation	Moderate	High
Feedback	High	Moderate
Mobility	Low	High
Comfort	High	Good
Multi-modality	NA	High

Table 4
Spectrum of power dissipation in medical applications [40].

Type	Application	Power	Rationale for power
Perpetual	Implanted in body Bridge monitoring	$< 10\ \mu W$	Micro-scale energy harvesting is primary source
Ultra-low power	Implanted in body In the ear On the skin	$100\ \mu W$ 1 mW 10 mW	Size and battery life Ear size Ability to dissipate heat
Power-Efficient	In the pocket Rechargeable, portable	100 mW 1–10 mW	Battery life of 10–14 h on one AAA cell
High performance	AC powered	> 10 W	Plugged in

Table 5
Power consumption data for some common energy monitoring sensors [42].

Wireless product	Current consumption			Battery voltage (V)	Power consumption (mW)
	Transmission mode (mA)	Receiption mode (mA)	Sleep mode		
RCS-S09U Universal ISM Band FSK Transceiver Module	15–26	11–15	$0.3\ \mu A$	2.2–3.8	33–78
G-Link 2.4 GHz wireless Accelerometer Node (Micro Strain)	25	25	0.5 mA	2.7	92.5
IMOTE2 (Crossbow)	33	33	$390\ \mu A$	4.5	127.05
XBEE Zigbee/802.15. 4 Modules (DigiInternational)	50	50	$10\ \mu A$	2.8–3.4	155
DataBridge wireless I/O modules	37–120	37–120	$< 100\ \mu A$	2.7–3.6	116.55–378
Apex and Apex LT Modules	170	37	$5\ \mu A$	2.1–3.6	105.45–484.5
Lt Series Transceiver Module	12–14	12–14	$11.5–20\ \mu A$	2.1–3.6	34.2–39.9
Si4420 Universal ISM Band FSK Transceiver	13–26	11–5	$0.3\ \mu A$	2.2–5.4	41.8–98.

clustering can be upgraded by considering energy harvesting process's characteristics [59].

3.4. Energy storage technology

It is not only a tough task to substitute the sensors implanted inside big and permanent structures, like buildings and bridges, but also batteries have restricted recharge cycles, so that they are not rechargeable beyond a threshold [60,61]. For these reasons, sensors with self-powered capabilities are necessary for long time sustainability. In that case, super capacitors can be an alternative form of energy storage [62]. Super capacitors can be re-energized by energy harvesting devices and can also substitute the batteries as the energy storing device [63]. The charge cycle of a super capacitor can be more than half a million with a 10 year functioning lifetime before the energy capacity is reduced to 80% [64]. Energy storage density is the main difference between the capacitors and super capacitors. In super capacitors, energy is deposited at higher energy density and its small form factor is more suitable for WSNs than a normal capacitor.

4. Challenges for design and evaluation

In the following subsections, we have briefly discussed some WSN research issues.

4.1. Power requirements in sensor networks

According to the Moore's law, as the integrated circuit technology progresses, each segmentation of integrated circuit chips is becoming physically smaller than their predecessors [65]. As a result of this tendency and for the reason of consistency, the supply voltage (VDD) is also reduced. The net outcome is the drop in energy consumption as a result of the parasitic component size reduction. For a scale decreased by an aspect α ($\alpha > 1$), the energy consumption of a shrunk circuit is condensed by $(1/\alpha)^3$, as discussed in [66].

The consumption of power can be scaled ensuing two different scenarios:

i. *Maximum performance use*: the development in technology permits to shrink the time per service for the use in a higher number of services. In this circumstance, the entire power consumption is scaled as $(1/\alpha)^2$.
ii. *Constant number of services*: the development in technology decreases the time per service and power consumption, but the user does not escalate the required service number. The power consumption for the processing functions is scaled as $(1/\alpha)^3$.

The power consumption of a WSN node can be divided between the various functions of the node. A number of authors

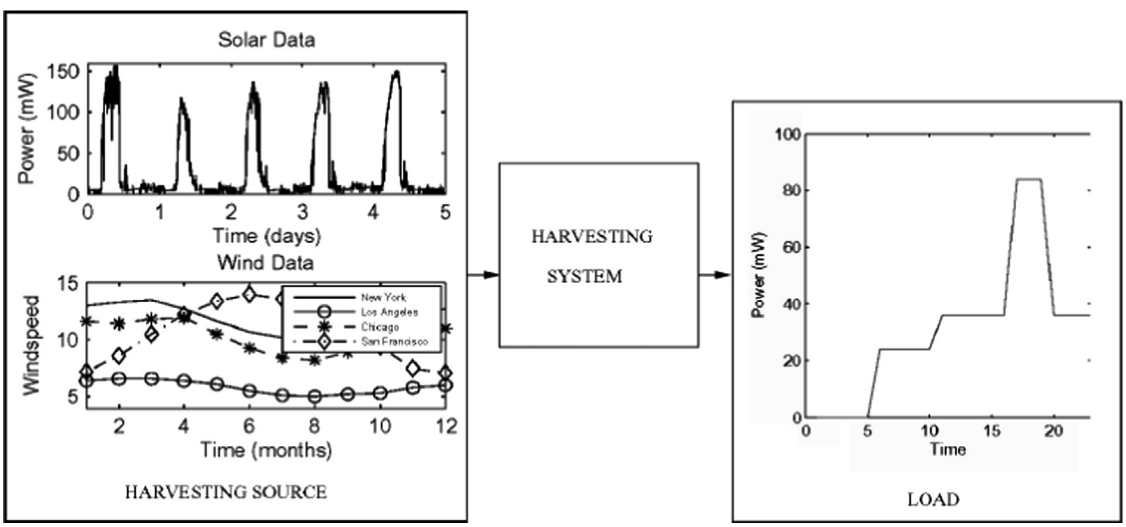

Fig. 5. Harvesting energy from the environment [47].

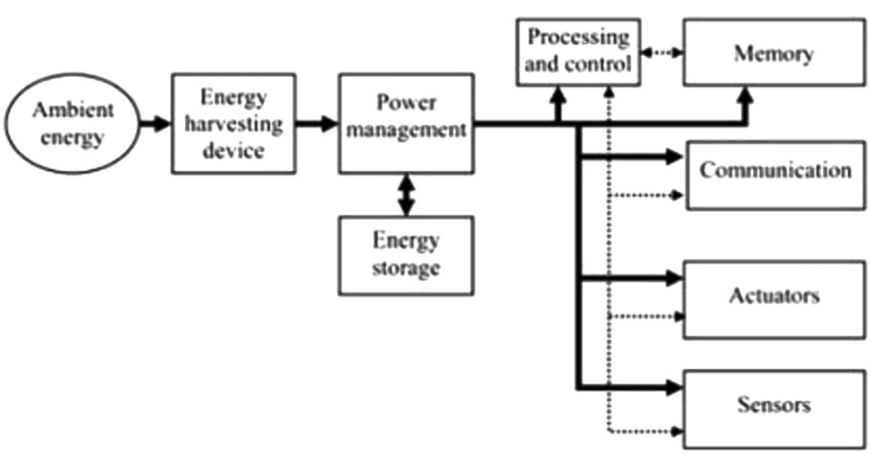

Fig. 6. A generic sensor network node with energy harvesting device [7].

have defined the organization of a WSN node [67]. The fundamentals of a WSN are explained in Fig. 6. It should be noted that all of these elements will not be present in all kinds of nodes. Each of the elements requires power depending on the specific application and therefore, the generalization about most power consumed parts is difficult. For example, if the actuators exist, it consumes a huge percentage of entire power. In addition, consumption depends on the operating mode of the device and how regularly it transmits and receives data. The split of power consumption is deliberated in Correal and Patwari [68] for a typical node and settled that a large percentage of total power is consumed by the communication functions.

4.2. Processing

The choice of processor is a key issue in finding the size and power consumption of node [69]. The main responsibilities of the processing unit are the controlling of data acquirement, management of the communication protocols, planning and preparation of data packets for transmission after collecting, filtering, and coordinating the information from the sensors. The power consumption and performance of the processor are controlled by the architecture, technology, and clock speed [67].

4.3. Communications

A variety of wireless communication standards exist in WSN [70]. The suitable standards are chosen using the factors of power requirements, inter-node distance, network structure's flexibility, data rate, time consumption for communication inauguration and the cost of implementation. The extensively used standards are grouped within the IEEE 802.11 standard for wireless local area networks (WLANs) and the IEEE 802.15 standard for wireless personal area networks (WPANs). For precise communication protocols, Wibree and ZigBee, Z-wave [7], and the communication standard developed by EnOcean [7], are frequently used standards.

The IEEE 802.15 has two key objectives: the area around a node that usually spreads up to 10 m in every direction and on forming a specification for low cost, low power, short range, and very small size radio transceivers. On the other hand, the WPAN standard is further classified into three different classes based on the rate of data, drainage of the battery and quality of service (QoS), and these are high rate WPAN, medium rate WPAN, and low rate WPAN [7,38,71].

Examples for the consumption of power of a selection of commercial WSN nodes are shown in Table 6 [7]. The values specified in Table 6 are based on an operating system where the communication is for 1% of the time, processing is for 10% of the time and the remaining time is for sleeping.

From the above table, it can be observed that during sleep mode, the consumption of Intel IMote2 varies significantly than Crossbow MICA and Jennic JN5139. Also, RX, TX and the only processor mode also consume more resulting a greater average power consumption in Intel IMote2 than the other two, but less than the general consumed power from other commercial sources.

4.4. Power conditioning circuits

The energy that can possibly harvest from the environment is discontinuous in nature. Therefore, not only the adjustment of the voltage level has to be done, but also there must be specific technique to stock the energy for using during the convenient time. This storing component can be a secondary battery or a capacitor.

The mentioned discontinuous nature of energy harvesting has significances on the operation of the electronic devices [72]. As a result, the electronic devices will work only when the energy storage element has adequate energy. In practice, we can differentiate two circumstances:

1. The consumption of power of the electronic device is inferior to the power delivered by the environment. In this situation, the operation of the electronic device will be continuous.
2. The consumption of power of the device is larger than the power delivered by the environment. In this case, the operation will be discontinuous, and the time in between the operations will be determined by the stored energy of the device.

4.5. Topology control

Transmission power regulation can be exploited by topology control techniques for aggregating the probability of productively transporting the data to the subsequent node [73]. More energy is essential to be harvested for higher transmission power and thus, it reduces the duty cycles of the node. This is necessary when the

Table 7
Overview of the discussed sources.

Main types of ambient energy	Discussed sources
Radiant energy	(i) Electromagnetic radiation and radio frequency (RF) (ii) Magnetic field (iii) Sun
Thermal energy	Temperature gradients or variations
Mechanical energy	(i) Vibration (ii) Motion (iii) Steady state energy (iv) Intermittent energy

Table 6
Summary of power consumption of commercial sensor network nodes [7].

	Crossbow MICA	Intel IMote2	Jennic JN5139
Radio standard	IEEE 802.15.4/Zig Bee	IEEE 802.15.4	IEEE 802.15.4/Zig Bee
Typical range	100 m (outdoor), 30 m (indoor)	30 m	1 km
Data rate (kbps)	250 kbps	250 kbps	250 kbps
Sleep mode (deep sleep)	15 μA	300 μA	2.8 μA (1.6 μA)
Processor only	8 mA active mode	31–53 mA[a]	2.7+0.325 mA/MHz
RX	19.7 mA	44 mA	34 mA
TX	17.4 mA (+0 dBm)	44 mA	34 mA (+34 dBm)
Supply voltage (minimum)	2.7 V	3.2 V	2.7 V
Average	2.8 mW	12 mW	3 mW

[a] Consumption depends on clock speed selected between 13 and 104 MHz.

neighbors of a node have not harvested enough energy for operation. Therefore, controlling of the transmission power is crucial for the performance optimization of WSN-HEAP (Wireless Sensor Networks Powered by Ambient Energy Harvesting). This also effects the rational topology and deployment approaches [74].

4.6. Mac

Usually, MAC protocols are planned for reducing the energy usage of WSNs and extend the lifetime of the WSN at a cost of extended delays [75,76]. It makes more logic in case of WSN-HEAP for finding the proficient use of the harvested energy in maximizing the output and minimizing the delays. Moreover, a slotted CSMA (Carrier Sense Multiple Access)-based MAC has been exposed in [77], which shows worse performance than an unslotted system. This is because; the energy is spent in the slot synchronization procedure, which results in a lengthier harvesting period by reducing the output.

4.7. Routing

As the estimation of accurate wakeup time of any sensor cannot be made because of the precise rate of the harvested energy alters of time and other ecological factors, it is very challenging to confirm that the succeeding node is awake for receiving a packet [78]. As a result, transmission and opportunistic systems are further appropriate for WSN-HEAP. However, transmission might outcome in several replicas if many nodes are awake. Hence, certain procedure of replication suppression is necessary for ensuring that during transporting the replicas, the harvested energy is not lost. If there are inadequate awake advancing nodes, then it turns into an irregularly linked mobile network. In this case, delay-tolerant network (DTN) techniques can appropriately be used [79].

4.8. Reliable data delivery

For some of the applications, reliable data delivery is the prerequisite. As the source node is not awake continuously, reliable transport protocol design is a challenge [79]. Additional prerequisite for ensuring every flow acquires its reasonable portion of bandwidth given the quantity of energy that can be possibly harvested from the environment. Thus, for variation of the data flow, there is a requirement for a transport protocol such that every source will acquire its reasonable share of bandwidth, no matter where it is situated in the WSN [79].

5. Different solutions and approaches

Electrical power is the prerequisite for operating a WSN and assumed that sometimes the nodes are installed in remote locations. In this case, it can be challenging to deliver a satisfactory huge stock of energy or to substitute the source of power at suitable intermissions. Even though the technology of non-renewable energy, for instance batteries and fuel cells, has developed over the years [66], this development is honestly slow associated with other regions of electronics [80]. Hence, they cannot fulfill the entire concurrent burden of long life, small volume, small weight and restricted environmental influence.

There are many sources of energy which can be measured for energy harvesting [81,82]. In order to attain a preferred power level, some transformation devices can be properly scaled. Though it might be probable to scale up a transformation device, small and light weight nodes are required for many WSN applications. Thus, power density is an important consideration, which can be accomplished.

A number of authors have proposed different suitable energy sources for harvesting. In [6], energy sources are clustered as human and environmental with sub-classes of kinetic and thermal. Buren [83] has presented an analogous grouping of energy sources as thermal energy, radiant energy, and mechanical energy sources. The authors of [84] have further classified the energy sources into three classes: radiant energy, thermal energy, and mechanical energy. Here, we are going to discuss about different energy harvesting sources compatible for WSN applications based on this classification. Table 7 is a summary about the sources that we are going to deliberate here and has opportunities to be used in WSN.

5.1. Electromagnetic radiation and RF energy

There are some regions of the electromagnetic spectrum of very high ambient energy levels and also some other regions of lower ambient energy levels. The conversion efficiency of electrical energy is also dependent on the portion of the considered spectrum [85].

Analysis of electromagnetic waves shows that the power density produced by an antenna is approximately equal to E^2/Z_0, where Z_0 is the radiation resistance of free space (377 Ω) and E is the local electric field strength in volts/meter. Thus, a 1 V/m electric field gives up 0.26 μ W/cm^2. However, this order of electric fields is uncommon except when close to a powerful transmitter [86]. A solution to this problem can be the deliberate transmission of RF energy only for the use of powering devices. This practice is commonplace in Radio Frequency Identification System (RFID) which derives energy inductively, capacitively or radiatively from the tag reader.

Table 8
Specifications of the power harvester module by power cast [88].

Product type	WPR 9006	WPR 2407
Efficiency (%)	70	70
Voltage range (V)	1.2–6	1.2–6
Current output (μA)	160	23
Frequency	900 MHz	2.4 GHz

Table 9
Comparison of power harvesters in the UHF RFID band [97].

Reference	Frequency (MHz)	Number of stages in the RF-DC voltage multiplier	DC-DC charge pump	Rectifier load (kΩ)	Sensitivity for 2.4 V output voltage (dBm)	Peak efficiency (%)	Fabrication process
[97]	866.5	4	Yes	3	−14	16	Discrete components
[98]	915	5	No	180	−8	30	Discrete components
[90]	900	16	No	100	−11	60	0.25 μm CMOS
[99]	920	4	No	330	−8	n.a	0.18 μm CMOS

Table 10
Magnetic field energy harvesting for different core configurations [88].

Type of coil	No. of turns	O.C. voltage at 200 A primary current (V)	O.C. voltage at 1000 A primary current (V)	Max. harvestable power (mW)
Rogowski coil	18	0.03	0.16	8
28 AWG wire wound on a wooden core	200	0.24	1.21	29.8
28 AWG wire wound on a hollow semi cylindrical silicon steel core	250	0.37	1.77	210.2
28 AWG wire wound on a flux concentrator	300	0.50	2.64	257
Flux concentrator connected to a transformer	300	12.5	70.6	225

Table 11
Market survey of magnetic field based energy harvesting products [88].

Product	Specifications
Power Line Sensor (Protura)	– Sends the information using GPRS. – Powered by a special designed two-piece transformer, which scavenges power from the magnetic field around the transmission line. – The harvesting circuit powers the sensor when the current in the line is more than 55Amp, while below this value of current the auxiliary supply powers the device.
Power Donut (USi)	– It transmits data on demand using GSM wireless cell phone technology. – Operates on the harvested energy for current above 50 A in the line.

There are two different principles on which RFID tags are powered - Active and Passive [87]. Active RFID tags are powered by batteries. Passive RFIDs derive power autonomously using the RF signals from the base station. The passive concept is used in the WPT and WPR series Power Harvester module manufactured by Power Cast [88]. The specifications are shown in Table 8.

Though RF signals can be used for powering the inactive electronic devices, such as RFID tags, these need to be sensibly regulated to the frequency of the radio source and are normally proficient to transmit power over a few meters distance [89]. Without using such a devoted source of RF energy, the ambient levels are very small and are ranged over a wide spectrum. The efficient far-field energy harvesting [90] uses a passively powered RF-DC conversion circuit operating at 906 MHz to achieve the power of up to 5.5 μW. In a related work [91], the authors consider the little available RF energy while utilizing it to power the sensor networks. Bouchouicha et al. [92] studied ambient RF energy harvesting in which two systems, the broadband without matching and narrow band were used to recover the RF energy.

RFID technology has experienced rapid growth in various applications, such as access control, public transportation, logistics, airline baggage tracking [93–95], etc. A simple RFID system includes a reader and a number of transponders (tags). Usually, passive RFID tags work in a shorter range and lower frequency, while longer distance applications are dominated by active tags [96]. A block diagram of an RF energy-harvesting system and reference design is described in [97]. A brief comparison of power harvesters in the UHF RFID band is shown in Table 9.

From the table, two great strengths are exhibited, one is the adoption of a DC-DC charge pump to further increase the rectified DC voltage and another one is the use of low-cost off-the-shelf discrete components.

5.2. Magnetic field

For energy harvesting from the magnetic field, a number of strategies have been suggested in the prior art. Some of the currently available products that harvest energy from the electromagnetic fields include the power donut and power line sensor. Moghe et al. [88] studied the electric and magnetic field energy harvesting for WSNs. Their work begins with a market survey on the power consumption of a selection of wireless communication devices. Experimental testing for magnetic field energy harvesting conducted by Moghe et al. of various cores and winding configurations is shown in Table 10 [88]. The maximum power generated is found to be 257 mW.

Lee et al. [100] have demonstrated a permanent magnet and vibration driven energy harvester for a self-powered system. The proposed harvester is made of permanent magnets (NdFeB), a planar spring, and a cylindrical-type copper coil. The proposed harvester is capable of generating a maximum output power of 1.52 mW for a resonance frequency of 16 Hz. El-hami et al. [101] presented a generator made of a permanent magnet core mounted at the tip of a planar steel beam. The results show an output power of 0.53 mW from this device. Due to the smaller size of this device, it is constructed without using micromachining techniques. Li et al. [102] has described a micro machined generator made of a permanent magnet by mounting on a laser-micro device spring structure. This device occupies around 1 cm^3 space and generates 10 μW of power at 2 V DC.

The products available in the market that use this technique of energy harvesting are presented in Table 11.

Table 12
Market survey of solar based energy harvesting products [88].

Product	Temperature difference (°C)	Open circuit voltage (V)	Power
Thermo Life (Thermo Life Energy Corporation)	10	11	135 μW
TMG127 (Kyrotherm)	100–20	2.6	458 mW

5.3. Solar energy

Solar energy harvesting has been prevalent for a long time and has become a mature technology now. Solar energy can be harnessed with the help of a PV system that converts sunlight into electricity. Solar panels are characterized by two parameters, the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}). A battery acts as a voltage source, whereas a solar panel behaves as a

voltage limited current source. As the amount of incident solar radiation decreases (increases), the value of I_{sc} also decreases (increases), however, V_{oc} remains almost constant. Due to its current source-like behavior, it is difficult to power the load system directly from the solar panel. Hence, an energy storage element, such as a rechargeable battery or an ultra-capacitor, is used to store the energy harvested by the panel and provide a stable voltage to the system.

The ordinary solar insolation at the top of the earth's atmosphere is nearly 1370 W m^{-2} [103]. The obtainable harvesting energy at a specific site on the earth's surface varies with daytime, latitude of the position, conditions of the atmosphere, and the conversion efficiency depends on the photovoltaic (PV) device's incidence angle. Yearly, received energy from the surface differs between about 300 W m^{-2} near the equator to about 100 W m^{-2} near the poles. For temperate regions, the day-to-day average obtainable shortwave energy differs from around 25 MJ m^{-2} day^{-1} in summer to 1–5 MJ m^{-2} day^{-1} in midwinter [104]. It is given that the commercially available PV cells have usual efficiency of about 15% and the minimum average electrical power is around 2 W m^{-2} over a full day period at a moderate site. A significant concern in the harvesting of solar energy is that the necessary energy is provided for only some parts of the day and assuming, the WSN will function at the same day times, the gathered energy must be put in storage for night time use [105]. By considering the similar moderate site as considered above, a total 0.15 MJ m^{-2} electrical energy can be harvested over an 8 h period in the day time of winter and essentially be put in storage to deliver for the leftover 16 h on the day. Thus, an average power of around 200 W m^{-3} can be deposited over a 24 h period. For a $10 \times 10 \times 10$ mm^3 capacitor, this amount would match up to an average power of 0.2 mW, which is within the range of usual WSN nodes functioning in sleep mode. The ambient light levels in indoor atmospheres are usually meaningfully inferior than outdoors with a usual light level of around 1 W m^{-2} equivalent to about 0.15 W m^{-2} of electrical energy [106].

A perennial supply of sunlight is necessary for harvesting solar energy which may not be feasible all the time. Moreover, solar cells suffer from the major disadvantage of very low efficiency of energy conversion. Single crystal solar cells have efficiencies of about 15% for commercially available cells and over 20% for high-end research cells. Thin-film polycrystalline cells exhibit efficiencies of 10–13%. Thin-film amorphous silicon solar cells have a lower efficiency ranging from 8–10%, but are well suited for indoor applications, as their spectral response closely matches that of fluorescent white light. Efficiency of cadmium telluride (CdTe) cells ranges from 8–13%, however, thin-film CdTe solar cells are widely used due to their good performance under a wide range of light conditions [88,107,108]. PV modules are quite popular and a plethora of products is available in the market. A brief description of popular products with specifications is listed in Table 12.

Nowadays, a lot of researches are ongoing for making an integrated system using solar cell and antenna, which can afford a more compressed surface area for smaller systems. Therefore, a lot of configurations have been suggested by different researchers for minimizing the degradation in both the solar and microwave performances [109–112]. The first stated integration superimposed of an indefinite silicon (Si) type solar cells onto a microstrip patch antenna of 2.225 GHz [110]. A 5.5 mm separation distance was kept between the solar cell's boundary and radiating patch edges for reducing the suppression of the electric fields. The authors of [111] have described an increased measure of integration. They have achieved an enhanced solar cell overlay with amorphous-Si (a-Si) developed directly on the ground plane of a 4.1 GHz slot antenna made of stainless steel. The idea of stimulating radiation directly from a GaAs solar cell at 2.75 GHz is stated in [112] and the application performance of a monocrystalline Si solar cell as a 1.575 GHz GPS antenna is described in [113]. The microwave energy was aperture coupled into the solar cell for radiation of both designs. In [114], the microstrip ground plane was replaced by a typical Si solar cell beneath a metallodielectric reflect-array for an 8.5 GHz horn-reflector antenna. Recently, a polycrystalline-Si solar cell ground plane underneath a 2 GHz quarter-wave shorted metal plate antenna upheld 96.54% of its PV output regardless of the shadow-casting of the 10 mm profile [115]. The performance of printed antennas over solar cell ground planes will mostly hinge on disruption of the microwave surface-currents by PV component.

Among all antenna types, microstrip patch antennas have been used comprehensively for both the simplest and most demanding microwave applications. They are economical to manufacture, conformable, lightweight and mechanically rugged, and their behavior is comparatively simple to predict [116–118]. As thin amorphous Si technology on polymer substrates established, a better level of combination was accomplished with the opportunity of cutting the cells to fit into composite geometries, like slot antennas [119]. Other efforts to incorporate solar cells with antennas have considered the viability of using the conductive contacts of monocrystalline Si solar cells as the radiating elements for a Global Positioning System (GPS) and Global System for Mobile (GSM) vehicular antenna [120].

5.4. Thermal

A thermal gradient is required for energy extraction from a thermal source [121]. The conversion efficiency from a thermal source is restricted by the Carnot efficiency to

$$\eta \leq \frac{T_h - T_c}{T_h}$$

where T_h is the absolute temperature on the “hot” side of the device, and T_c is the absolute temperature on the “cold” side.

Thus, the efficiency of the energy conversion becomes higher with greater temperature difference. A prospective heat source for a lot of environments would be a room heater. A hot water radiator usually provides almost 1.4 kW m^{-2} when heated to 50 °C above

Table 13
Market survey of thermal based energy harvesting products [88].

Product	Specification and features	
	Rated output voltage at 1000 W/m^2	Rated current at 1000 W/m^2
Sensor Transmitter Module STM110 (Enocean)	– Solar cell Power RF transmitter module. – Operates at 2 V – Operation in darkness > 60 h	
Solio Hybrid 1000 (Solio)	6 V	165 mA

the ambient temperature and thus, a fairly small amount of such a radiator may possibly deliver an operational power source. The use of body heat is considered by Starner [103,122], but fairly small variance is observed between the body temperature (37 °C) and ambient temperature (20 °C), thus limiting the Carnot efficiency to 5.5%. The total body area can only produce 6.4 W from the total of nearly 116 W dissipated by a usual human during sitting [123]. The use of some body parts would decrease the resulting power, and since blood movement would be reduced in the enclosed area, the obtainable energy would reduce more. Starner [122] determined that a device with wrapping just the neck could possibly provide 0.2–0.32 W. Moreover, the obtainable energy is affected by the thermal resistance of the source and the thermal energy sink.

Another thermo-electric energy harvester is the thermo-electric generator designed and familiarized by Pacific Northwest National Laboratory [124]. This generator is used to convert environmental thermal energy into electric power for variable applications that demands low power usage. Applications of this energy harvester are diverse, containing automotive performance monitoring, homeland and military security surveillance, and agricultural management. Arian et al. [125] have designed a passive network, built by using low threshold voltage chip diodes and capacitors. This system produces a dual supply voltage from one of the coils using the temperature deference to power up the active rectifier. That proposed system supplies 54 μW to a 37 μA load over a dual rail 1.46 V DC voltage with a total system efficiency of 81%. The maximum overall system power density has been confirmed to be 6.06 μW/cm^3.

A survey of the thermal energy harvesting products was performed and results are shown in Table 13 [88].

5.4.1. Solar thermal for low electrical power applications

Solar thermal electricity can be defined as the outcome of a process by which directly collected solar heat is transformed into electricity by using some kind of heat to the electricity conversion device. Solar collectors are the mainly used device for this solar–electricity conversion. There are low, medium and high temperature solar heat collectors, based on the collecting temperature [126]. Low temperature collectors are usually flat plates without having any focusing device. This type of collectors can collect temperature up to 80 °C. They can be used for providing heat to swimming pools and spacing heating, etc. Generally, the heat transfer media are air or water. Medium-temperature collectors are at a temperature level from 80 °C to 250 °C. This temperature can be collected by a flat plate collector with well insulation and solar collector with reasonable concentration. With high solar concentrating ratio, the temperature of the solar collector can reach as high as 800 °C for high temperature collector.

Flat plate or evacuated tube solar collectors can be used to gather solar energy in a non-concentrated mode for heating and cooling [127]. Due to high efficiency and cost effectiveness, this technology is receiving worldwide popularity. This technology may be used year round, even in high humidity, cold temperatures, and/or poor weather conditions [128]. Partly due to their better efficiency over electric water heating [129], as of 2010, over 70 million residences worldwide had active installations of this technology [130]. Hybrid photovoltaic/thermal (PVT) collectors [131,132] concurrently transform solar energy into electricity. A typical PVT collector contains of a PV unit with 5–10% peak efficiencies. Performance comparisons between the hybrid PVT collectors and conventional PV systems specified that the hybrid PVT schemes can attain better energy transformation efficiency with prospective cost benefits [131,133]. For low temperature transformation, evacuated tubes and organic Rankine cycle (ORC) are also broadly used technologies in the solar thermal area [126]. Generally, the evacuated tubes are used for producing solar hot water. These types of tubes can be used up to 185 °C temperature and the overall efficiency for this system is 10–13%. Nguyen et al. [134,135] have described a prototype of the low temperature ORC system. According to their suggestions, this system could be used cost effectively for distant areas with good solar radiation.

Table 14
Typical temperature and concentration range of the various solar thermal collector technologies [134].

Technology	*T* (°C)	Concentration ration
Air collector	0–50	1
Pool collector	0–50	1
Reflector collector	50–90	–
Flat plate collector	30–100	1
Advanced flat plate collector	80–150	1
Combined heat and power solar collector	80–150	8–80
Evacuated tube collector	90–200	1
Compound parabolic CPC	70–240	1–5

Table 14 shows the concentration range of various solar thermal collector technologies.

5.5. Vibration

Vibration energy is convenient in most of the built environments [136]. The vibration amplitude and its frequency are the factors on which the energy mining from vibration sources depends. It also relies on the amount to which the existence of an energy harvesting device distresses the vibration. This consecutively relies on the harvesting device mass, which is relative to the vibrating mass. Vibration sources differ significantly in amplitude and dominant frequency [137]. Measurement for a number of vibration sources have been presented in Roundy et al. [138], which show that the amplitude and frequency varies from 12 ms^{-2} at 200 Hz for a car engine compartment to 0.2 ms^{-2} at 100 Hz for the floor in an office building with the majority of sources measured having a fundamental frequency in the range 60–200 Hz. Vibration existing in most of the environments is made up of a number of frequencies instead of a single frequency.

Another significant matter is that the dominant vibration frequency relies in many circumstances, on the functioning parameters of the apparatus, which causes the vibration. Thus, for example, the dominant vibration frequency on a domestic fan varies when partial obstruction of the air flow is occurring. Correspondingly, testes on an energy scavenging node deployed for the extraction of energy from a pump of a marine vessel shows that the energy production fell significantly because of the fluctuations in pump speed [139].

Kim et al. [140] has described the use of a piezoelectric cymbal transducer for generating electricity by using the vibration of car engine. The efficiency of this system was found to be 7.5%. After connecting this device with rectifier, smoothing capacitor, and buck converter, the maximum output was found almost 30 mW. For charging the car battery from this harvested energy, much higher power level is needed. Clark et al. [141] has suggested a force-driven piezoelectric generators for the medical applications. They intended to get the input energy from the fluctuating pressure in a blood vessel. They have worked with a square sheet of 1 cm^2 made of the piezoelectric material and for the 1 Hz frequency, they harvested around 1 μW. Yates et al. [142] reported the measured result for an inertial generator using the vibration of a flexible membrane. The authors have found almost 0.33 μW harvested energy for 4.4 kHz input vibration. The research group of the Chinese University of Hong Kong [143] has reported an electromagnetic generator using vibration and found 40 μW of power for an input vibration of between 60–120 Hz.

Edward et al. [144] have described a novel WSN system that harvests the vibrations created by passing traffic on a bridge. This vibration is transformed into functional electrical energy by means of a linear electromagnetic generator, which allows harvesting of up to 12.5 mW of power with an excitation frequency of 3.1 Hz. A different mechanical energy harvesting based on the electrostatic micro generator was suggested by Sterken et al. [145]. In this system, a micro electrostatic converter comprised of a vibration sensitive adjustable capacitor was polarized by an electret and it revealed that power generation competences up to 50 μw for 0.1 cm^2 surface area was attainable. Enrico et al. [146] have proposed an active electronic interface for an energy harvester comprising a vibration based electromagnetic transducer. The transducer delivers a peak voltage of 3.25 V when functioned close to its mechanical resonance frequency about 10.4 Hz.

A survey of the energy harvesting products based on mechanical vibrations was performed and summarized in Table 15 [88].

5.6. Steady state mechanical sources

The steady state ambient energy sources are based around the fluid flow, as water current, either in natural channels or over pipes, or based around uninterrupted motion of an object, such as a rotating shaft. Fluid flow based mechanical energy sources are extensively used for electrical power generation on a macro scale, such as in wind turbines and hydroelectric plants [147]. This can also be considered for the application of smaller scale energy harvesting. Starner [122] introduced the prospective of energy harvesting using blood flow and inhalation in human and found that substantial power was obtainable.

The fundamental mechanisms of flow energy harvesting using oscillating foils have been studied for several decades. It was initially established that a flapping foil was proficient of mining energy from an oscillating current [148]. Additional works exposed that a stationary foil, while immersed under incoming waves, could drive itself onward using energy mined from the wave-generated flow [149]. Energy harvesting using a flapping foil from a uniform flow has also been explored [150]. Hoffmann et al. [151] have designed the radial-flux energy harvester to the housing of a conventional mechanical water flow meter permitting the use of standard apparatuses, such as housing and impeller. The energy harvester is capable of generating up to 720 mW at a flow rate of 20 l/min. A minimum flow rate of 3 l/min is obligatory to start the harvester. In this case, a power output of 2 mW is attainable. Singh et al. [152] have assessed the possibility of harvesting energy from fluttering slender elastic structures. This study led to the amazing result that the optimal for the bi-articulated shape is very dissimilar from the continuous optimal.

5.7. Intermittent mechanical sources

Some available energy may be cyclic in nature and from those sources, the energy is only obtainable for a small part of the cycle. The energy found from the vehicles passing over an energy harvesting device is an example of this type [7] and irregular human movement, such as walking or typing. Table 16 shows the possible energy harvesting from human.

Energy harvesting from these intermittent sources was also reflected by Starner [122] who decided that the obtainable energy is ranged from about 7 mW from the movement of the finger during typing to 67 W for the movement of the lower limb.

It might be calculated that a subject weighing 60 kg must put on a force of at least 588 N over the foot in the time of walking (the highest force is normally 25% above the weight of a body in time of walking and up to 2.75–3 times body weight in time of running [154]). If this force is attended by a 10 mm floor or shoe deflection, then the obtainable energy will be 5.88 J and supposing two steps per second, an available power of 5.88 W per foot. Alike calculations can be done for vehicles crossing over a deflection device. The far superior weight of the subject will result in a significantly greater energy level. Table 16 shows the summary of mechanical energy harvesting.

Harkanwal et al. [155] have proposed a fitness monitoring system with energy harvesting from body movements for transmitting signals through wireless antenna. Glynne et al. [156] used a cantilever for harvesting energy. Results investigated by Glynne et al. [156] displays a non-uniform distribution of strain in the piezoelectric material while a properly tapered cantilever formation can ensure uniform strain. The device confirmed an equitable total of power for a given volume of piezoelectric material using a tapered cantilever.

A large number of research groups are currently active in the field of motion-energy harvesting, and a wide range of devices and applications have been reported. Here, we will discuss about the human and machine motion and the gyroscopic motion.

5.7.1. Human and machine motion

Biomechanical energy harvesting using human motion has a great promise to be a clean substitute for electrical power provided by batteries for mobile electronic devices. Human power has a strong benefit of being always obtainable, necessitating no

Table 16
Summary of potential energy for harvesting from human [42,153].

Activity	Watts
Sleeping	81
Lying quietly	93
Sitting	116
Standing at ease	128
Eating meal	128
Strolling	163
Driving car	163
Playing piano	163
House keeping	175
Carpentry	268
Hiking, 4 mph	407
Swimming	582
Mountain climbing	698
Long distance run	1048
Sprinting	1630

Table 15
Market survey of vibration based energy harvesting products [88].

Product	Maximum harvested power (mW)	Frequency (Hz)
Volture Piezo Energy Harvester-PEH20W (Mide)	20	50–150
VEH-APA400M-MD (Cedrat)	95	110
PMG27 Microgenerator (Perpetuum)	4	17.2
VEH360 (Ferro Solutions)	10.8	60
Energy Harvesting Shoe (Scientific Research Institute)	800 mW of power per shoe at a pace of 2 steps per sec	

chemical fuel or distinct logistical measures, and having a little heat signature. It is proven that harvesting energy from human motion not only uses unused energy, but also can really increase the biochemical efficiency through negative work cycles. This is much like regenerative braking for humans.

The direct force generator is the main type of motion energy harvesters. The first stated research in this generator is found in a patent literature [157]. The patented device contains an RF *TX*, which functions at the power generation rate. Practically, direct force type micro-generators are first observed in Umeda et al. [158]. Gonzalez et al. [66] detected that almost 1.2 W energy is possible to harvest from human walking and 78 mW could be due to the spreading of the chest during breathing. Paradiso et al. [159] explored the energy harvesting from the shoes at the time of running or walking. The author defines three dissimilar types of energy generators for shoes: a piezoelectric bender positioned in the sole, a uni-morph attached to the bent steel plate, and a rotational electromagnetic generator in the heel. Using these three types of generators, around 2 mW, 8 mW, and 250 mW energy was harvested, respectively, which was used to powering an RFID tag.

Table 17
Comparison between various motion based energy harvesters proposed by different researchers.

Author	Ref.	Input frequency (Hz)	Power density (μW/cm^3)	Harvester effectiveness (%)	Volume figure of merit (%)
Electromagnetic motion harvester					
Ching	[143]	60	830		0.64
Mizuno	[174]	700	0.2 × 10–3	0.42 × 10–3	2.26 × 10–6
Glyne-Jones	[156]	322	44.0		0.003
Beeby	[175]	9500	0.21	2.6 × 10–3	3.27 × 10–5
Beeby	[176]	350	47.5	0.90	0.15
Serre	[177]	360	0.07		1.6 × 10–5
Huang	[178]	100	40	0.14	0.08
Electrostatic motion harvester					
Mizuno	[174]	743	1.23 × 10–3	6.6 × 10–6	1.86 × 10–9
Arakawa	[179]	10	15	7.42	0.68
Despesse	[180]	50	56	7.66	0.06
Yen	[181]	1500			
Tsutsumino	[182]	20			
Miao	[183]	20	4	17.9	0.02
Piezoelectric motion harvester					
Roundy	[106]	120	80	7.3	0.39
Hammond	[184]	40	145		1.25
Lefeuvre	[185]	56	88		
Fang	[186]	609	3510		1.39
Elvin	[187]	0.5	2.47		
Ng	[188]	100	82		0.03
Mide	[72]	50	198		0.16

Donelan et al. [160] have explained the energy harvesting probability from knee bending. The device they proposed was stretched over a substantial part of the leg for generating large torque and the output power was 7 W for normal walking motion.

Electromagnetic inertial generators are a different kind of motion harvester. Mitcheson [72] first introduced this kind of harvester in 1970, which was the first report of a self-winding watch. This was the key idea behind the Seiko Kinetic watch, which is a commercial product. Chandrakasan et al. [161] have used human walking motion and almost 400 μW energy was harvested. Some other researches have been also found in [72] for electromagnetic inertial generators.

The other kind of motion generator is the piezoelectric inertial generators. The first reported work in this technique was the contribution of Segal and Bransky [162]. Elvin et al. [163] have deliberated a piezoelectric based self-powered strain sensor. In [164], the authors describe an enhanced piezoelectric generator where 375 μW was generated for 2.25 m/s^2 acceleration at 60 Hz.

5.7.2. Gyroscopic motion

Now a day's gyroscopic energy harvesting technology is also well established. In gyroscopic motion, the magnitude of the inertia relies not only on the size and density of the proof mass, but also on its rotational velocity. The latter parameter is not directly controlled by the device dimensions. However, gyroscopic action delivers a way to significantly boost the capability of a mass to resist alterations to its position. This is the foundation of its significance in navigation instruments. Thus, it is worth investigating the prospective of gyroscopic motion for energy harvesting. This has been presented for the first time in [165].

Gyroscopic precession that rises from an input torque producing a deviation in the spin axis of the flywheel can deliver an effective means of energy generation, which can be used in motion control of autonomous underwater vehicles and stabilization of bicycles, cars, monorails, buildings, robots, and boats [166–169]. This technique also exploits on spacecraft for the control of attitude and power storage [170]. A prototype scheme of a gyroscopic point absorber containing a single gimbaled flywheel with a vertical spin axis, attached to a floating structure moored to the seabed, is introduced in [171]. A gyro wave triggered power generator including two or more single gimbal control moment gyros on a floating body is described in [172]. Though there has been several recommendations about applying gyroscopic systems to harvest wave energy [168], available theoretical and experimental confirmation is inadequate for WSN application. So, there is a great opportunity to utilize this technology for WSN applications.

A gyroscopic system was deliberate to capture the rotational movements using the mouse ball in order to generate and harvest electric power [173], where the generator is powered through

Table 18
Comparison of energy harvesting sources for WSNs **[84]**.

Energy source	Classification	Power density	Weakness	Strength
Solar power	Radiant energy	100 mW/cm^3	Require exposure to light, low efficiency for indoor devices	Can use without limit
RF waves	Radiant energy	0.02 μW/cm^2 at 5 km	Low efficiency for indoor	Limitless use
RF energy	Radiant energy	40 μW/cm^2 at 10 m	Low efficiency for out of line of sight	Limitless use
Body heat	Thermal energy	60 μW/cm^2 at 5 °C	Available only for high temperature difference	Easy to build using thermocouple
External heat	Thermal energy	135 μW/cm^2 at 10 °C	Available only for high temperature difference	Easy to build using thermocouple
Body motion	Mechanical energy	800 μW/cm^3	Dependent on motion	High power density, not limited on interior and exterior
Blood flow	Mechanical energy	0.93 W at 100 mmHg	Energy conversion efficiency is low	High power density, not limited on interior and exterior
Air flow	Mechanical energy	177 μW/cm^3	Low efficiency for indoor	High power density
Vibration	Mechanical ENERGY	4 μW/cm^3	Has to exist at surrounding	High power density, not limited on interior and exterior
Piezoelectric	Mechanical energy	50 μJ/N	Has to exist at surrounding	High power density, not limited on interior and exterior

Table 19
Comparison between different energy harvesting devices[a].

Device	Output power (μW)	Frequency (Hz)	Amplitude (ms^{-2})	Normalized power (μW)	Volume (mm^3)	Ref.
V-Pz	2.1	80.1	2.3	0.5	125	[189]
V-Pz	210	120	2.5	28	1000	[190]
V-Pz	375	120	2.5	50	1000	[138]
V-Pz	0.6	900	9.81	0.0007	2	[191]
V-Es	3.7	30	50	0.005	750	[192]
V-Es	1052	50	8.8	27	1800	[193]
V-Es	70	50	9.2	1.7	32	[193]
V-Em	0.3	4400	382	4.7[a]10–8	5.4	[142]
V-Em	180	322	2.7	7.7	840	[156]
V-Em	4000	100	0.4	25,000	30,000	[7]
Em shoe insert				60,000	56,000	[159]
Em shoe insert				90,000	97,500	[7]
Thermoelectric				50	41	[7]
PV cell (outdoor)				20,000	500,000	[7]
PV cell (indoor)				1500	500,000	[7]

[a] V → vibration, Pz → piezo, Es → electrostatic, and Em → electromagnetic.

exploiting rolling energy by mouse dragging. This proposed harvester was projected to power the electronic system of a mouse device, for example the ultra-low power RF *TX* and microcontroller. The total energy produced using the harvester was higher than 3 mW, which was adequate for the operation of wireless mouse in a transmit range of one meter.

Comparison between different motion harvesters described by different researchers is presented in Table 17.

5.8. *Comparison between different energy sources*

Table 18 demonstrated comparisons between different energy harvesting sources. This table provides information on power density for different energy harvesting sources. It also shows the weakness and strength of the energy sources. These data will be helpful for choosing a proficient source for our desired WSN applications.

A comparison between energy harvesting devices used for different sources is presented in Table 19. From Table 19, we will get a clear view on the power output from different devices. According to this information, we can decide the scope of future development in energy harvesting devices.

6. Conclusions and future works

In this paper, we have discussed about energy harvesting in the context of scopes, challenges and approaches. It is now well defined that energy harvesting can be the alternative source of energy supply for a more reliable system using for remote and unreachable areas. This possibility is increasing the scope of energy harvesting in WSN and encouraging plenty of innovative research areas. Review of related literature shows that numerous researches have been conducted over the last decade for establishing standard techniques of energy harvesting and also, the researches are ongoing. The energy deficiency solutions strongly depend on this energy harvesting scheme. We have reviewed existing projects conducted by all research communities involved in this field and we have studied their advantages and weaknesses. Furthermore, we have studied issues that are still open and have proposed possible solutions and directions for future works. A lot of work should be done in future to improve the harvesting energy system for WSNs. Some possible works may be:

i. The complete integration of the energy harvesting circuit block with ultra-low power RFID circuitry.
ii. More reliable and cost effective production systems are needed with more advanced micromachined embodiments.
iii. Progresses are required in order to decrease the percentage of the generated power used for power management.
iv. The development of new applications using low-power sensors, such as acoustic, pressure, and strain sensors will be investigated.
v. Exploring applications of the on-board computational power, for compression and other embedded sensor data processing functions for energy harvesting from mechanical, thermal and vibration sources, is another area for future research.

Energy harvesting system for WSNs has a great prospect in near future. This paper will enlighten the researchers to work with endeavor and have a brief look into the summaries of recent works.

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